Five basic mistakes to avoid when using instrumentation amplifiers

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Instrumentation amplifiers (in-amps) show up in a broad spectrum of applications: measuring heart signals, factory monitoring equipment, aircraft controls, and even animal tagging. Engineers have found them to be a simple and effective way to amplify small signals and remove power-line noise. Unlike ADCs, with their modes and registers, a typical in-amp has only two adjustments: gain and reference voltage. Unlike op amps, where poor feedback design means oscillation, in-amps are quite stable.

The instrumentation amplifier's ease of use can lead to a sense of complacency. While it is easy to get an in-amp up and running on the bench, poor attention to detail can lead to mediocre performance in the field. Since the in-amp is typically connected directly to a sensor, designers must think about the full range of signals this sensor could present. This article will cover five cases that often trip up designers.

RFI rectification

Instrumentation amplifiers are often connected to an external sensor through leads of several feet or more. These leads act as a sensitive antenna: picking up both 50/60 Hz noise as well as much higher frequencies.

Most modern monolithic instrumentation amplifiers reject almost all 50/60 Hz common-mode noise. In fact, common-mode rejection (CMR) is a key specification and is prominently displayed in most in-amp datasheets. It is typically specified from dc to 60 Hz. Depending on the architecture, an in-amp may be good at rejecting mid-frequency interference. An example of good mid-frequency rejection is 80 dB CMR at 10 kHz, which is the performance of Analog Devices' AD8221 in-amp.

Modern monolithic amplifiers are not very good at rejecting higher common-mode frequencies, **Figure 1**.

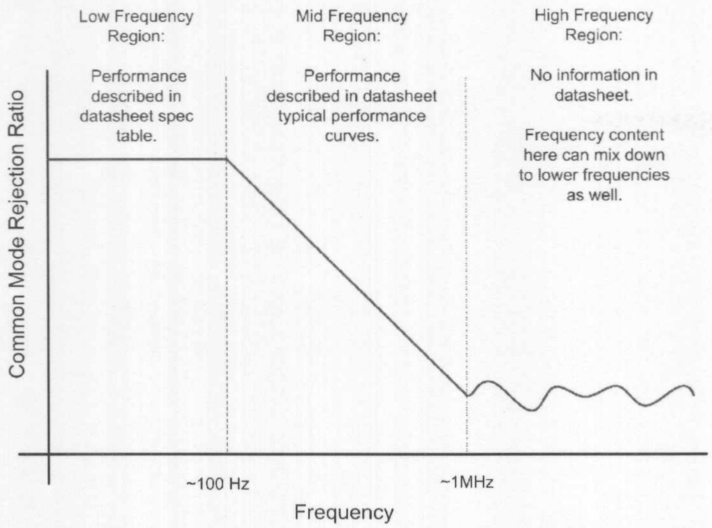

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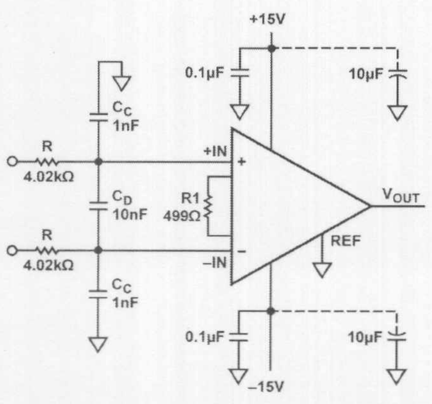
Figure 1: An instrumentation amplifier's common-mode rejection capability varies dramatically with frequency.

Instrumentation amplifiers are designed to be low-current, precise devices. The tradeoff for the low current and precision is speed. Most instrumentation amplifiers are simply not fast enough to faithfully track fast common-mode signals.

Not only do instrumentation amplifiers have a hard time reducing the amplitude of the high-frequency signals, they also distort them as they pass through the amplifier. This distortion, known as radio frequency interference (RFI) rectification, can create lower-frequency products in the band of interest. This is why high-frequency ac content can result in dc offsets.

The solution is to prevent the high frequencies from reaching the in-amp in the first place. This can be achieved by placing a low-pass filter before the instrumentation amplifier. **Figure 2** shows such a filter.



$$\text{Differential Filter Cutoff} = \frac{1}{2\pi R(2C_D+C_C)}$$

$$\text{Common Mode Filter Cutoff} = \frac{1}{2\pi RC_C}$$

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Figure 2: Placing a filter before the in amp eliminates high-frequency signals before they are rectified by the amplifier's front end.

Resistors should be chosen to meet noise versus voltage protection tradeoffs (see *Voltage Protection* section below). The differential capacitor (C_D) should be chosen to place the differential frequency cutoff slightly higher than the signal of interest. Finally, the common-mode capacitors (C_C) should be large enough so that the low pass filter formed by R and C_C adequately rejects the RFI interference.

The C_C capacitors should match each other as closely as possible. Any mismatch will result in different low-pass filter characteristics for the two inputs. Even slight mismatches are enough to reduce mid-frequency CMR. Since smaller capacitor values create less absolute mismatch, the choice of C_C capacitors is a tradeoff between RFI filtering protection and CMR at mid-frequencies.

A typical guideline is to make the C_C capacitors at least 10 times smaller than the C_D capacitor. For the C_C capacitors, high-accuracy COG type capacitors are recommended over X7R types, because the values will track each other more closely. The accuracy of the C_D capacitor is much less critical.

Note that in some cases of very strong RFI signals, the interference may not come in through the input leads but, instead, through other pins or through the package itself. In these cases, the problem may need to be addressed at the source of the interference or through shielding.

Common mode range

Just like op amps, in-amp datasheets have entries in the specification table titled "Input Voltage Range" and "Output Voltage Range", or something similar. This can be misleading. Even if the circuit is designed to keep the input and output signals inside their respective ranges, the amplifier may still not function as expected.

Most instrumentation amplifiers have two stages: a preamp stage, which amplifies the differential signal, and a difference-amplifier stage, which then removes the common mode. In between the two stages are nodes that must carry the combination of both the amplified differential signal and the common mode. It's possible these nodes can reach the supply rail value, even when the input and output are within their specified ranges.

Figure 3 shows how this behavior plays out with actual supplies and input voltages.

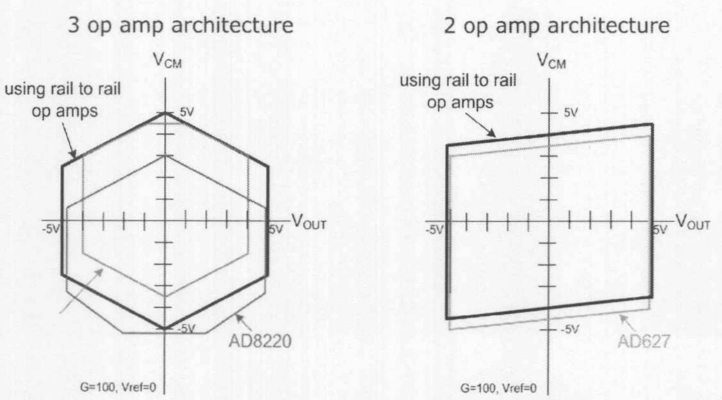

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Figure 3: The common mode vs. output voltage plot of in amp depends on the architecture; shown is the typical behavior of the two most-common architectures: the three op-amp and two op-amp in amp.

The two diagrams show the typical behavior of the most common in-amp architectures: the two op-amp configuration and the three op-amp configuration. The figures show the behavior of these architectures assuming ideal rail-to-rail op amps were used, as well as some actual monolithic parts.

How can a board designer know the true common-mode range? Older in-amp datasheets are remarkably silent on this issue, and it caused a lot of design headaches for in-amp users. Modern in-amp datasheets typically include graphs similar to those shown in Figure 3, or they provide equations. To test the

common-mode range on the bench, increase the common-mode voltage until the circuit gain seems to decrease. At this point, the voltage on one of the internal nodes has reached its limit.

As illustrated in Figure 3, different in-amps have different behavior. So, if one amplifier does not work in a specific application, try another. Another option is to reduce the gain of the instrumentation amplifier and compensate by applying more gain later in the signal chain. This strategy can adversely affect the system noise, CMR, and offset performance, however, so read the datasheet carefully.

It should be noted that IC manufacturers are developing architectures that do not have this internal node limitation. The AD8553 in-amp from Analog Devices is an example of such a product. One drawback of these new architectures is that they tend to have poorer noise performance at low gains than the traditional architectures.

Voltage Protection

In amps are often connected to sensors outside the circuit board. In actual use, these connections may be made to the wrong place, subjecting the in amp to voltages larger than intended. If the in amp is left unprotected, these large voltages will damage the amplifier.

It is often not the voltages, but the large currents created by these voltages, that cause the failure. A primary failure mechanism is metal migration: when the small metal interconnects in the chip erode away under high-current conditions. Metal migration is a cumulative process and is accelerated with heat, so amplifiers can typically tolerate shorts bursts of high voltages better than prolonged exposure.

The classic way to protect a circuit from overvoltages is to add resistors in series with the inputs. If the datasheet provides no other information, it is generally safe to assume that ESD protection diodes can handle at least 5 mA of current. The resistors should be chosen so that the maximum voltage drop between the input voltage and the in-amp supply causes less than 5 mA to flow into these diodes.

Unfortunately, resistors add noise. A 1 kΩ resistor has 4 nV per root Hz of thermal noise; a 100 kΩ resistor has 40 nV per root Hz of noise. It is important to remember that noise adds by the square root of the sum of squares: $\sqrt{(e_{n1}^2 + e_{n2}^2 + e_{n3}^2)}$, The total impact on the system noise is insignificant if the resistor noise is three to four times lower than the intrinsic in-amp noise.

In some cases it may be possible to use low-value resistors and then discrete diodes between the inputs and supplies to shunt current away from the part. The success of this strategy is highly dependent on the amplifier's input structure. Before trusting such a circuit in full production, it is important to determine on a prototype where the current flows during overvoltage conditions. Low-leakage, low-capacitance diodes are recommended to keep overall input error at a minimum.

Driving the Reference Pin

An in amp's output is created with respect to the voltage at the reference pin. This can be quite handy in single-supply applications, where the signal should be centered at mid-supply. Simply drive the reference pin to the required bias voltage.

For the vast majority of in amp, the reference pin must be connected to a low impedance: either ground or an amplifier output. A resistor divider simply won't do. Driving from a high-impedance source will result in poor CMR, **Figure 4**.

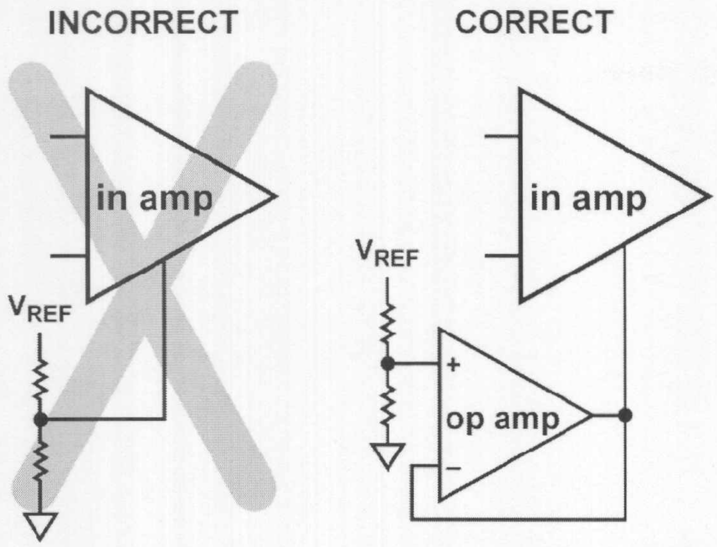

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Figure 4: To get the best CMRR performance out of an in amp, drive the reference pin with a low-impedance source or ground. Never tie the reference pin directly to a voltage divider.

A good guideline is to keep the dc impedance below 1 Ω.

Floating Voltages

Because an in amp has both a + and - terminal, it might be tempting to think of it as something like a mini-version of a handheld voltmeter. Unlike an isolated, handheld voltmeter, however, an in amp cannot measure floating voltages. This includes anything that is not referenced to ground: isolated thermocouples, secondary sides of transformers, and batteries. The bias currents of the in amp will pull any floating source out of the amplifier's common-mode range. This is what the data sheet means when it states that the amplifier needs an input bias-current return path.

A corollary rule is that an in amp with its inputs shorted does not necessarily produce zero volts at the output. The shorted inputs must also be connected to a voltage in the common-mode range of the amplifier. **Figure 5** shows ideas for typical floating sources.

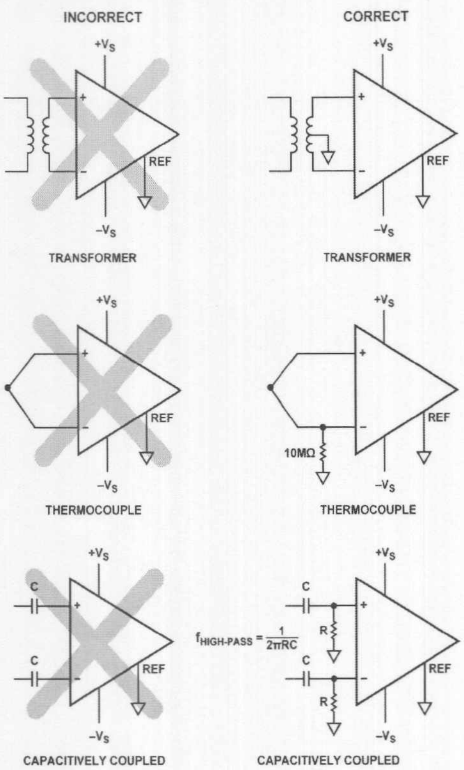

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Figure 5: In amps always need a bias-current path.

Because in amps are easy to use, they can usually be treated as simple black boxes. This article covered the five most common cases where a little deeper understanding can result in a more robust and reliable design. The **Reference** provides more detailed information about how instrumentation amplifiers work.

Reference

Kitchin, Chuck and Lew Counts. *A Designer's Guide to Instrumentation Amplifiers, Third Edition.* Analog Devices. 2006.

About the Author

Matt Duff joined Analog Devices in 2005 as an applications engineer in the integrated amplifier products group. Prior to joining ADI, Matt worked for National Instruments in both design and project management positions on instrumentation and automotive products. He received his BSEE from Texas A&M and MSEE from Georgia Tech. He can be reached at mattduffanalog@gmail.com.